THE NEW MILLENNIUM FORMATION FLYING OPTICAL INTERFEROMETER

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ABSTRACT

Spaceborne optical interferometry has been identified as a critical technology for many of NASA's 21 century science visions. Included in this vision are interferometers that can probe the origins of stars and can ultimately study Earth-like planets around nearby stars. To accomplish this feat, separation of an interferometer's collecting apertures by large baselines are required - from hundreds of meters up to thousands of kilometers. Thus the large separations require multiple spacecraft flying in a formation. Furthermore, optical pathlengths over these distances must be controlled to the nanometer level. This level of control demands precision spacecraft controls, active optics, metrology, and starlight detection technologies, To date, some of these technologies have been demonstrated only in ground applications with baselines of order of a hundred meters; space operation will require a significant capability enhancement. This paper describes the New Millennium formation* flying optical interferometer concept and associated *technologies. The mission is designed to provide a technology demonstration for multiple spacecraft precision formation flying and* very long baseline *optical interferometry. The interferometer would be distributed over three spacecraft: two spacecraft would serve as collectors, directing starlight toward a third spacecraft which would combine the light and perform the in terferometric detection. The interferometer baselines would be variable, allowing baselines of* 100 *m to 1 km in an equilateral formation, providing angular resolutions from* 1 *to 0.1 milliarcsec.*

INTRODUCTION

Many scientific goals of the 21st century in the fields of astronomy and astrophysics require order-of-magnitude advancements in optical angular resolution. Angular resolution improves linearly with the diameter of filled-aperture telescopes, or in the case of interferometers, with the distance (baseline) between widely separated apertures. Interferometers with baselines of 100 meters are being implemented on the ground, offering fairly high (1 milliarcsec) resolution of compact astrophysical objects. Many more of these objects, however, are faint and can only be detected by taking advantage of the enormous increase in sensitivity afforded by space-based observation, beyond the turbulent and partially opaque atmosphere. Among the key scientific goals enabled by space-based optical interferometry are submilliarcsec measurement of stellar diameters, resolution of close and interacting binaries, detection of extra-solar planets, and precise measurement of galactic and cosmic distance scales,

Optical interferometers collect light at separated apertures and direct this light to a central combining location where the two light beams interfere. Fringes produced by the interference provide amplitude and phase information from which a synthesized image can be generated. Space-based optical interferometers can be implemented as single monolithic spacecraft, in which small (10 to 30 cm) collecting apertures are separated by tens of meters; or implemented as separated spacecraft where baselines of hundreds, or even thousands, of meters enable measurement with very high (sub-milliarcsec) angular resolution. A separated spacecraft optical interferometer concept, referred to as the New Millennium Interferometer (NMI), is a simplified interferometer that demonstrates enabling technologies while still retaining science capabilities.[1,2] It has been identified as the third New Millennium deep space technology demonstration mission in preparation for a separated spacecraft implementation of the Terrestrial Planet Finder interferometer, along with other future exoplanet imaging and high resolution astrophysics precision formation flying missions.

MISSION DESCRIPTION

The NMI consists of three separated spacecraft forming art equilateral triangle, as shown in Figure 1. Two collector spacecraft direct stellar light to a third cornbiier spacecraft where the light beams are combined for interferometric measurements. NM1 will image bright astrophysical objects (14th magnitude and brighter) in the visible at 0.55 to 0.9 microns, with a 100 m to 1 km baseline to attain an angular resolution of 1 to 0.1 milliarcsec.

All three NMI spacecraft will be launched from a single launch vehicle into a heliocentric orbit in late 2001. After launch and interferometer checkout, the three spacecraft will be released and deployed into formation. The spacecraft w il 1 be separated up to 1 km, as permitted by diffraction at the metrology apertures; the baseline cart be reduced to 100 m by scaling down the formation triangle. A propulsion system is used for formation flying to ±1 cm in three transitional axes and to point each spacecraft to ±1 arcminute relative to one another. Two candidate propulsion systems are currently under consideration. One design uses traditional but small 4.5 mN cold gas (GN_2) thrusters. Art alternate design uses one form of electric propulsion. At a 3 Hz firing rate, a pair of Pulsed Plasma Thrusters (PPT) provides up to 4.2 mN thrust using Teflon propellant with an inherently higher specific impulse (I_{sp}) than cold gas. Either propulsion system for NMI design will be sized for around 50 to 100 target stars during its six month lifetime.

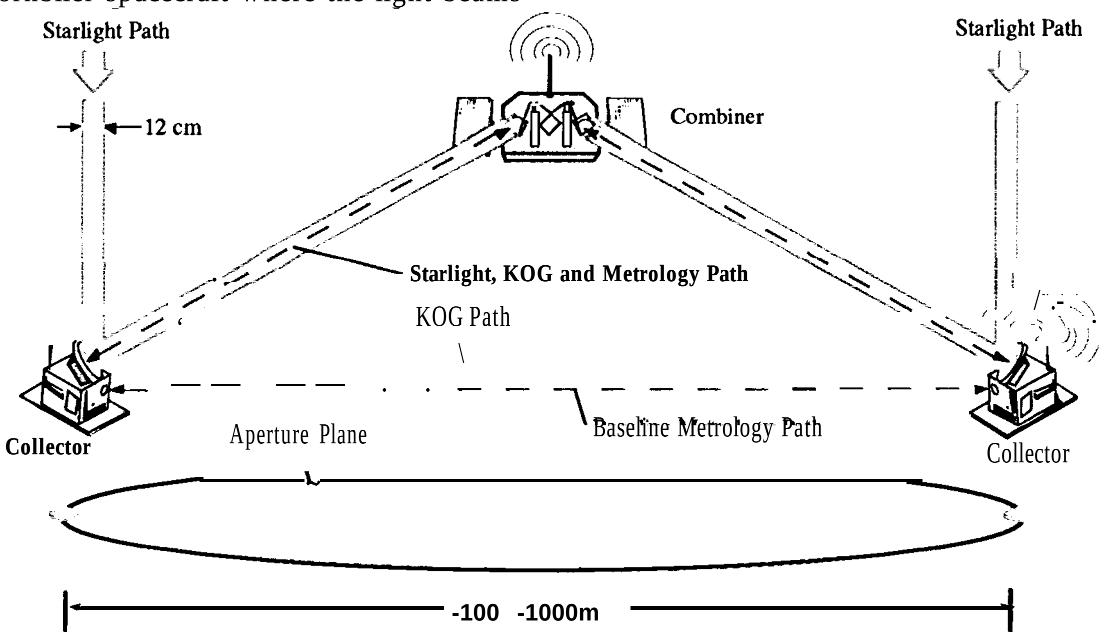

FIGURE 1. New Millennium Interferometer Concept.

Science Objectives

Compared to current and near future ground-based optical interferometers, NM I will have longer baselines (by a factor of at least 3), and will be able to see fainter sources (by ≈6 optical magnitudes). In addition, a more accurate calibration of visibility amplitudes will be possible, due to the lack of atmospheric coherence losses. NMI will therefore explore a large region of new parameter space on the sky, although with a limited total number of observations. Below are some of the key science observations that will be possible with the mission.

One **of the** simpler measurements involves Wolf Rayet stars. These stars are hot and luminous, and have very strong stellar winds (i.e. they are losing mass at a high rate). Current understanding of them is limited, although it is believed that they have evolved beyond the hydrogen burning (fusion) stage of stellar evolution. NMI would allow the imaging of the mass outflow in these objects for the first time, thus providing a quantitative test of their dynamics.

A more exotic target would be Cygnus X-1, one of the brightest X-ray sources in the sky. The X-ray emission is thought to arise when gas from a hot, luminous primary star (which one can observe) spills onto a black hole. Spectroscopic measurements show the gravitational influence of this unseen companion, but its mass is still unknown. Observations with NMI on baselines up to 1 km would allow measurements of the angular size of the primary star for the first time, and therefore determine the distance to this object much more directly and accurately than has been **done before. Simple shape measurements would** allow testing of the assertion that it fills its Roche lobe. Furthermore, by observing the changes in shape as the star rotates, one can determine the inclination of the orbital plane (of the two stars) to the line of sight. This unknown inclination is a crucial parameter in constraining the mass of the presumed black hole from Doppler measurements.

One of the crucial questions in astronomy concerns the age and evolution of the universe. Current estimates of the age of the universe (from measurements of the scale and rate of its expansion) appear to conflict with the ages of the oldest stars (i.e. the stars are older than the universe). The largest uncertainty in these stellar ages comes from errors in measuring the distance to the globular clusters in which they reside, NMI would reduce this error by calibrating a crucial measuring tool - RR Lyrae variable stars (which are found in globular clusters). The combination of measured radial velocities (through Doppler shifts **in their spectra) and measured angular size changes** (with NMI) would yield the distance to these RR Lyrae stars **in a very direct way.**

One of the most challenging of NMI projects involves Seyfert Galaxies and quasars. These objects exhibit broad (up to 1000 km/s) emission lines, arising from a compact region around the central nuclear source. Understanding this region is a key to the understanding of the energetic and dynamics of these sources. NMI would allow scientists, for the first time, to resolve this broad line region in a few bright, nearby Seyfert galaxies and the brightest quasar, 3C 273. The measurement is challenging because 1) these objects are near the 14th magnitude limit of NMI, and 2) it would require NMI to "phase up" on the unresolved continuum source in order to measure the visibility of the broad line emission region in several spectral lines (using the dispersed fringes on the CCD).

TECHNOLOGY DESCRIPTION

The principal technologies required to perform separated spacecraft optical interferometry for NMI are formation flying, precision control of starlight path, laser metrology, and interferometer phasing. Formation flying employs advanced controls and an imovative sensor which uses GPS technology for deep space.[3] The starlight subsystem is similar to those used in ground **interferometers, incorporating fast steering mirrors** and optical delay lines for high bandwidth t i 1 t and pathlength **control .45 Laser** metrology among the spacecraft provides equivalent structural rigidization similar to the approach for monolithic space interferometers.[6] Phasing of the interferometer uses a Kilometric Optical Gyro (KOG), which is a Sagnac interferometer employing counter-propagating laser beams among the three spacecraft.

Formation Flying

One design approach for NMI is to minimize the instrument to spacecraft interactions. The high bandwidth fine pointing and phasing control is provided by the instrument, with a dynamic range such that closed-loop spacecraft control is not needed. There is nominally no feedback between the interferometer internal control system and the spacecraft control system.

NMI requires spacecraft formation flying accuracy to ±1 cm and ±1 arcminute to avoid **saturation** of the **optical delay lines and collector flat mirror**

gimbals respectively. In addition, precision formation flying also provides: 1) baseline orientation changes, to rotate the instrument about the line-of-sight, sweeping out a chord in the aperture (u-v) plane; 2) change in formation size, to vary the angular resolution; and 3) retargeting the interferometer to point at other objects. Cooperative but centralized formation flying controls will most likely be used for NMI due to the small number of spacecraft along with mission cost considerations.[7,8,9,10] However, other imovative advanced formation flying controls, such as distributed, biological controls, etc., wi ll certainly be examined for NMI.[11]

Also key to formation flying is formation sensing of inter-spacecraft relative distances and angles. An imovative sensor concept, based on JPL TurboRogue™ GPS receiver technology, was developed for this and other applications. The Autonomous Formation Flying sensor (AFF) uses GPS-like signaling among multi-channel transceivers on the three spacecraft. Each spacecraft transmits a carrier and pseudorange signal which is received by multiple antennas on the other spacecraft. Multiple patch antemas on each spacecraft allows 4π steradian angular **coverage as well as** determination of relative angle and range. The accuracy for the AFF is better than ±1 cm relative distance and ±1 arcminute relative angle, consistent with the formation-flying requirements.[12,13,14]

Starlight Subsystem

The starlight subsystem begins with a flat mirror on each of the two collector spacecraft. Each mirror directs a 12 cm diameter beam of stellar light to the combiner, as shown in Figure 1, with corner-cube retro-reflectors located at the center of the mirror for use by the laser metrology system. Each mirror is mounted on a three-axis gimbal (tip, tilt and roll) with range to accommodate a 1 arcrninute spacecraft attitude deadband. Flat mirrors were selected for simplicity, allowing uniform array expansion when interspacecraft distances are increased. For a larger system a better approach is for the collector optics to produce a beam waist at the combiner spacecraft, so that only a single large optical element is required. This latter approach mandates a fixed collector to combiner separation, unless the curvature of the collector mirrors is made variable.

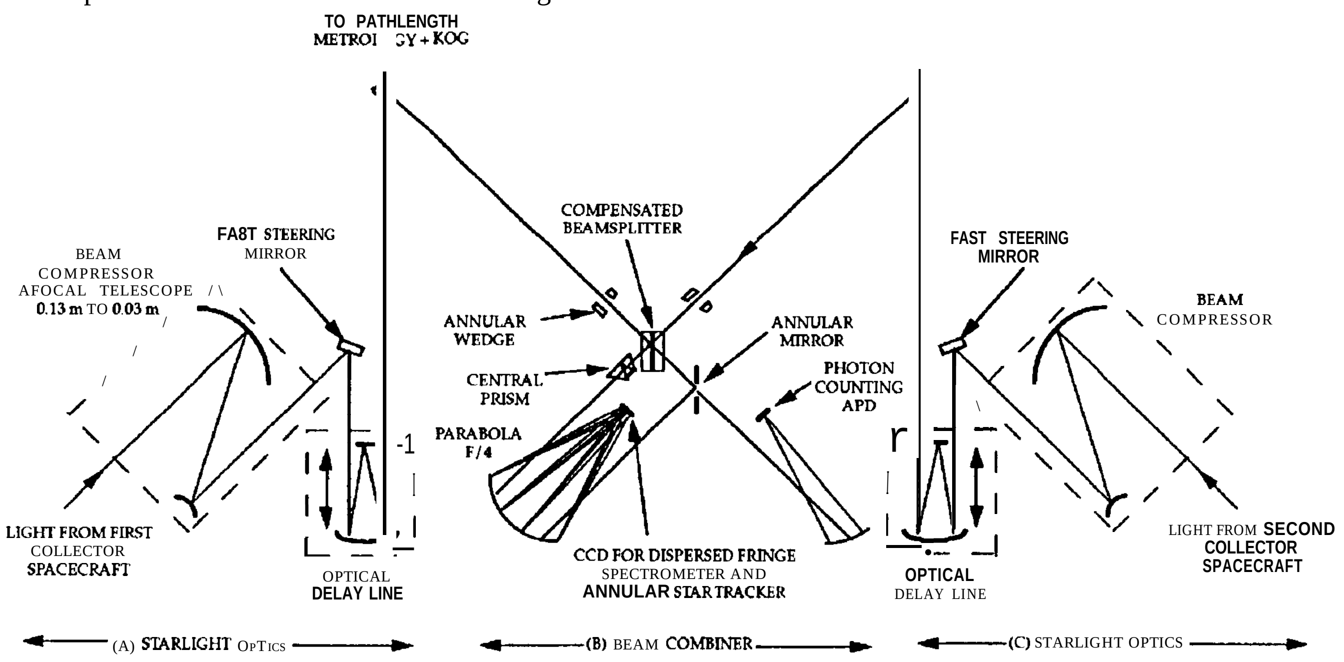

FIGURE 2. NMI Starlight Subsystem.

Figure 2 shows a concept for the beam combiner in the combiner spacecraft that is similar to systems used in ground interferometers. Section A illustrates the starlight optics on the combiner spacecraft: the collector starlight enters a beam compressor (a pair of off-axis confocal parabolas with 13 cm clear aperture), which compresses it to 3 cm diameter. The compressed beam is redirected by the fast-steering mirror (FSM), which provides high-bandwidth tilt control, onto an optical delay line (ODL), and then to the beam combiner. Starlight from the second collector spacecraft follows a symmetric optical path to the beam combiner, as shown in Section C. The ODL are used in each arm for fine pathlength control. A range in delay of 2 cm with nanometer resolution accommodates the formation-flying deadband without the need for nanometer control of spacecraft relative positions. The short delay-line range allows simplification by using of a two-stage (piezoelectric transducer (PZT)/voice-coil) system. Closed-loop pathlength control to less than 10 nm is routinely accomplished with ground versions of similar delay lines and is baselined for NML

Section B shows a concept for the interferometer beamsplitter and fringe-detection back end. The two outputs of a compensated beamsplitter feed different detectors: a photon-counting avalanche photodiode (APD) detector for high sensitivity fringe detection (for science), and a fast-framing Charge Coupled Device (CCD) (for fine guiding). The pupil of the beamsplitter output feeding the CCD is divided spatially between fringe sensing and shear sensing. The inner part of the beam passes through a direct-view prism, providing a dispersed fringe pattern on one line of the CCD. The annular portion of the beam is nondispersed, providing images of the two input pupils on the CCD. Annular wedge prisms in each arm offset the images from each other and from the dispersed fringe, allowing the same CCD to serve for both tilt sensing and fringe detection. Also shown in Figure 2 is the injection of the pathlength metrology and KOG, discussed in later sections. The ultimate sensitivity of the system is estimated as 14th magnitude, limited by the coherence time provided by the KOG.

Laser Metrology

The absence of a structure means that structural rigidity is achieved actively, rather than through reliance on the intrinsic stiffness of a truss. The sensors for achieving rigidity are the laser metrology systems which measure precise inter-spacecraft distances and interferometer component positions. As shown in Figure 2, laser metrology is introduced into the starlight path through a dichroic beamsplitter in the beam combiner, and measures the distance from the combiner to the comer cubes at the center of each collector's flat mirror. The third laser path is implemented separately between the two collector spacecraft where separate comer cubes (from the ones a-t the gimbal mirrors) can be used for this measurement. With these three metrology beams, the positions of the spacecraft can be controlled to the nanometer level to stabilize the interferometer. It is however more efficient to use the data for feedforward control to the optical delay lines for stabilizing the starlight path. This would correct for both baseline changes as well as internal pathlength changes. The delay-line range (2 cm) establishes the required accuracy of the stationkeeping of the individual spacecraft based on the implementation that there is no feedback between the delay-line control system and the spacecraft control system. Alternatively, with tighter systems coupling, the delay-line range could be reduced.

The metrology system would use heterodyne techniques which readily provide much better than 10 nm relative position accuracy. The laser source would nominally be a single-frequency device to provide a narrow linewidth in order to maintain coherence over the 2 km maximum round-trip propagation. Heterodyne implementation would use fiber-fed frequency shifters to provide the necessary frequency offset between polarizations.

Finally, there are two other metrology beams internal to the combiner spacecraft. These monitor the ODL positions in order to separate delay-line position changes from spacecraft position changes.

Ki ometri'c Optical Gyro

The conventional approach to point an interferometer so as to not to blur the fringe requires off-axis stars for sensing. However, it would be problematic with long baselines for two reasons. A small off-axis angle translates into a large delay change: 3 arcminute over a kilometer baseline is 1 meter of path delay, which is not easily accommodated with the NMI structure. In fact with the simple collector mirrors, the light would miss the combiner entirely. Thus, accommodating off-axis stars would require increases in complexity for both the collector and combiner spacecraft. The other reason that off-axis guide stars are problematic is because when long baselines resolve the nearby bright sources that would ordinarily serve as guide stars, reducing the available signal-to-noise ratio for tracking.

An alternative approach is to use an inertial sensor. The long baselines of **NM I allow for the use of a Kilometric Optical Gyro** (KOG). The KOG is a Sagnac interferometer employing counter-propagating beams among the three spacecraft - essentially a fiber-optic gyro where the fiber sensing coil is replaced by space, shown schematically in Figure 3. **The KOG measures** formation rotation at a highest precision. It is a particularly good match to the long baselines of a separated-spacecraft interferometer, as the sensitivity of the **KOG is** proportional to the enclosed area. The required interferometer pointing accuracy scales linearly with baseline, so that the KOG works better with long baselines.

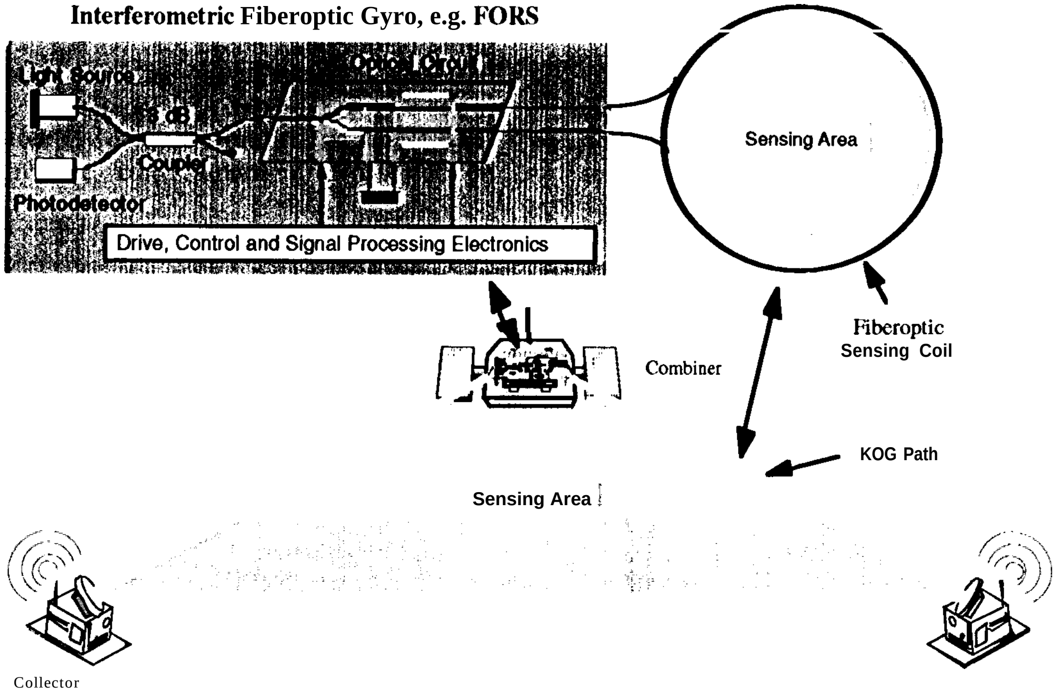

FIGURE 3. Kilometric Optical Gyro Concept.

During the mission, by monitoring separately the length of the individual legs of the triangle, it is possible to separate rotation from length change. This is the purpose for the ODL metrology system described in a previous section. While it is not needed for control reasons, subtraction of this measurement from the combiner to collector metrology can provide a precise measure of just the inter-spacecraft distance. The **KOG beam is** injected through a dichroic beamsplitter in the beam combiner, and propagates toward each collector, To reflect the KOG light around the loop of spacecraft, rather than back toward the s tells r source, a diffraction grating is placed on the collector mirrors. The grating is nominally implemented as a second-surface grating, with the first surface coating a dichroic to reflect starlight and transmit the KOG light. Pointing of the grating is accomplished using the roll axis of starlight gimbal. The gimbal is sensed using edge- and angle-sensors around the boundary. The KOG would nominally operate at 1.5 microns, distinct from the starlight and laser-metrology **wavelengths. The implementation of the KOG may be able to use a modified fiber-optic gyro sensor head, with changes to the internal electronics to accommodate changing loop pathlengths.**

CONCLUSION

The NMI concept is a simplified separated spacecraft interferometer with the goal of technology demonstration to enable future applications of interferometer and other multiple spacecraft formations. Key technologies presented for general space interferometry include precision starlight path control and laser metrology. Technologies for general formation flying spacecraft include formation controls, formation sensing and inertia phasing of formations.